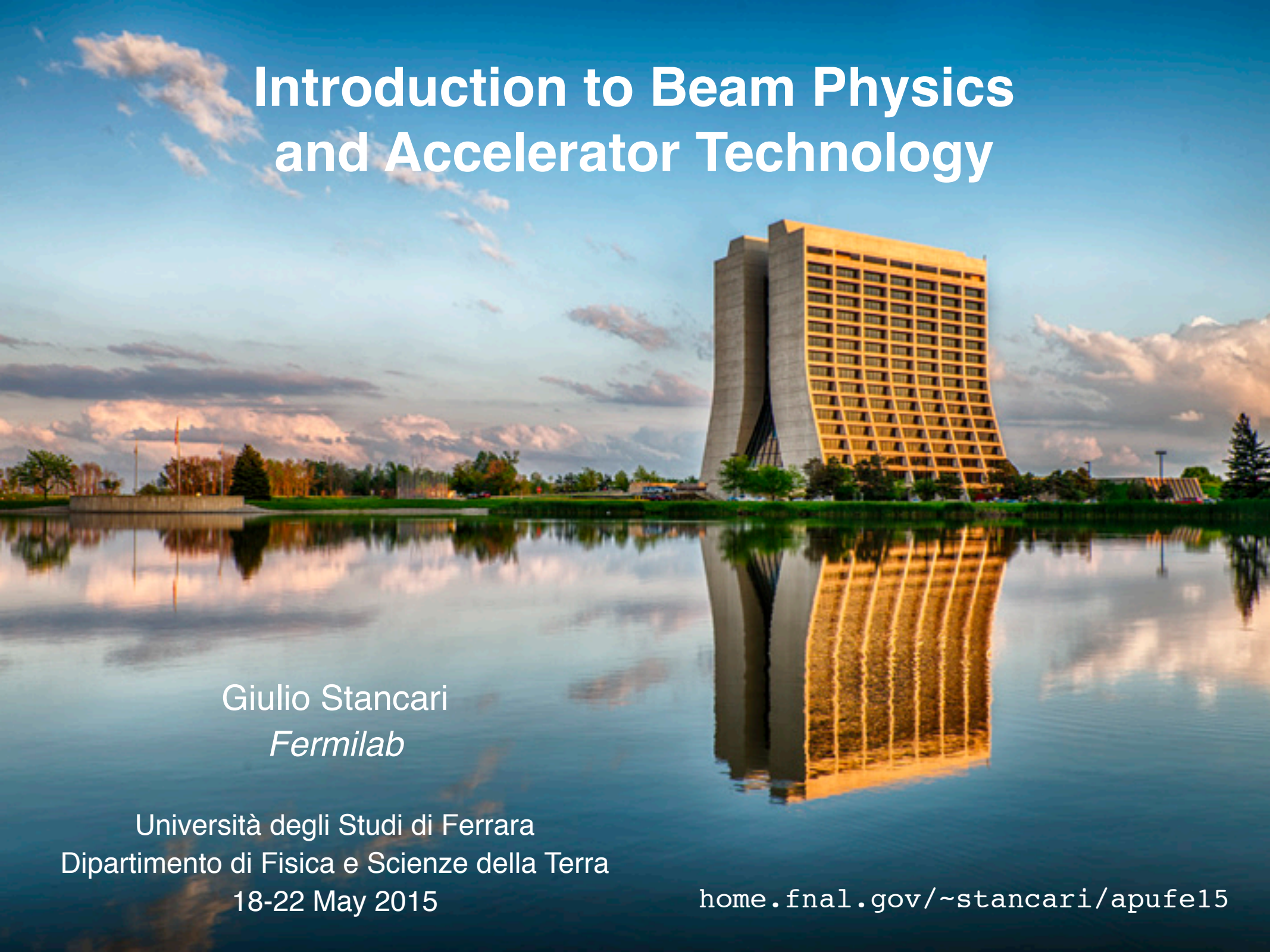
Introduction to Beam Physics and Accelerator Technology



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Fermilab

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Dipartimento di Fisica e Scienze della Terra
18-22 May 2015

home.fnal.gov/~stancari/apufe15

An overview

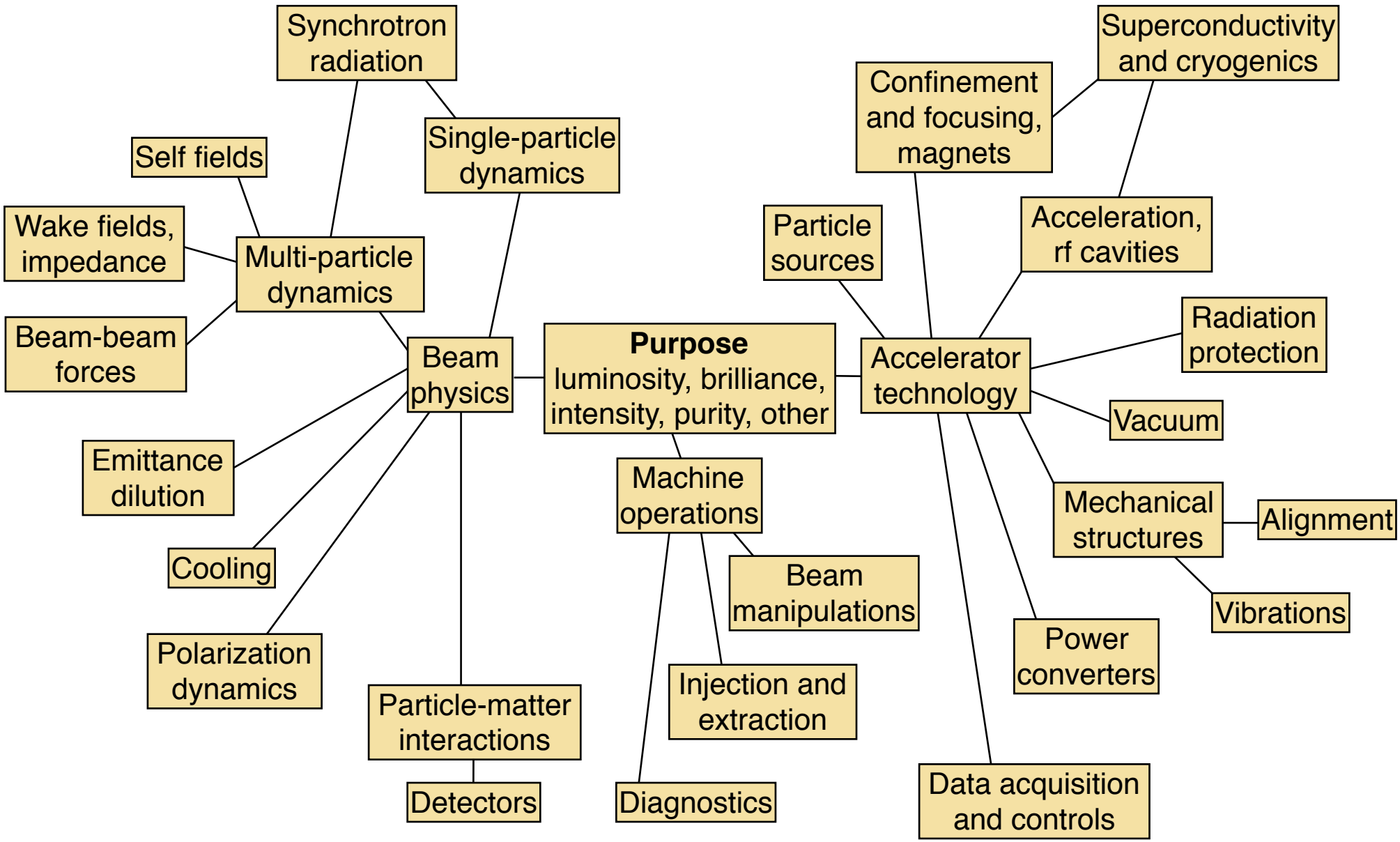
Questions driving current research

- What can we learn about nature from experiments at accelerators?
- Can we understand and control the behavior of intense charged-particle beams?
- Are there new ways to design accelerators?
- What technologies will improve performance and reduce cost?

Main applications of accelerators

- **Nuclear and particle physics**
  - synchrotrons, linacs, storage rings, colliders, ...
- **Biology and material science**
  - synchrotron radiation, neutrons, free electron lasers, ...
- **Medicine**
  - radiation treatment, hadron therapy, diagnostic isotope production, ...
- **Manufacturing processes**

The field of Accelerator Physics: a concept map



What do accelerator researchers talk about? A word cloud

Text from 1381 abstracts submitted to the 6th International Particle Accelerator Conference, Richmond, VA, USA, May 2015, `<www.ipac15.org>`

Resources

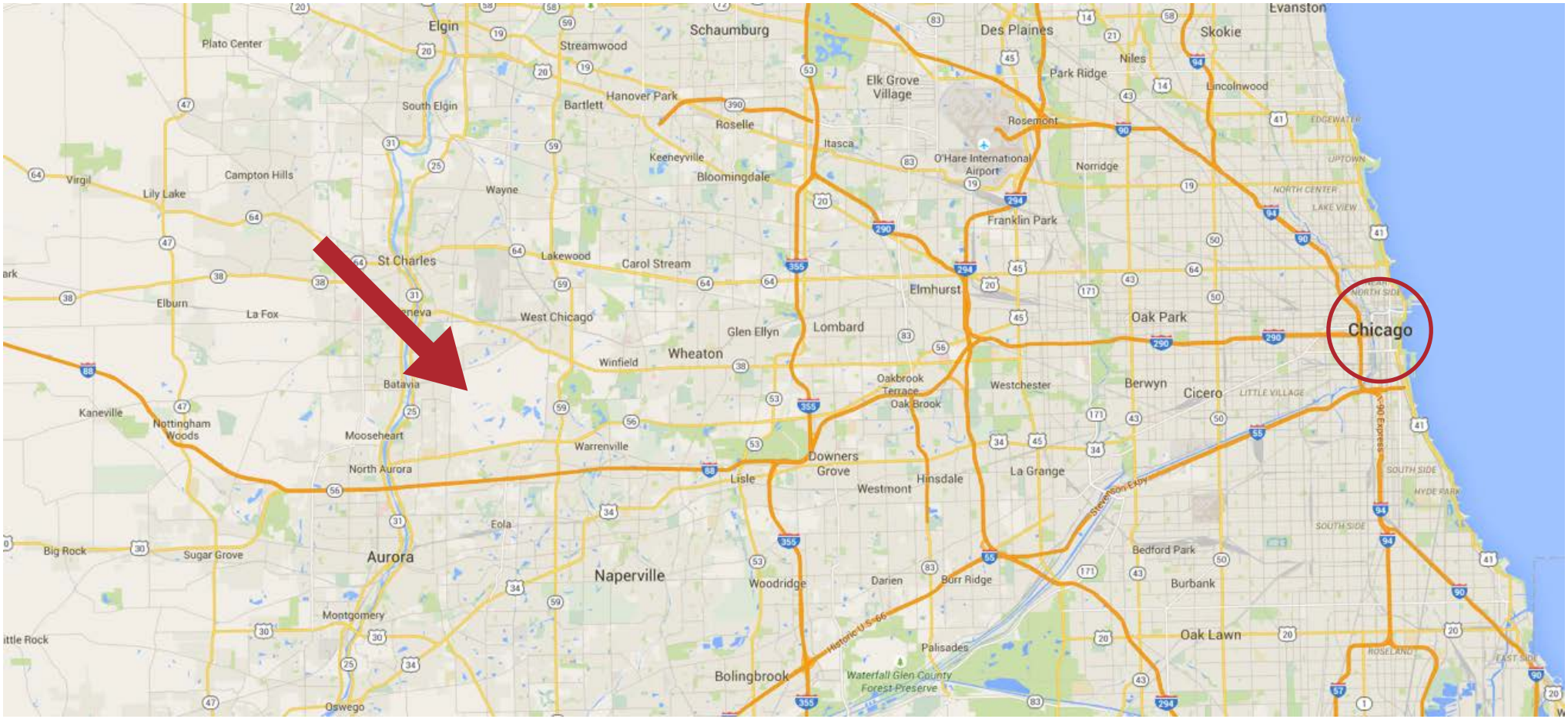
- Textbooks
- Schools
- Internships
- Journals
- Conferences

More information and links on course web site:

<home.fnal.gov/~stancari/apufe15>

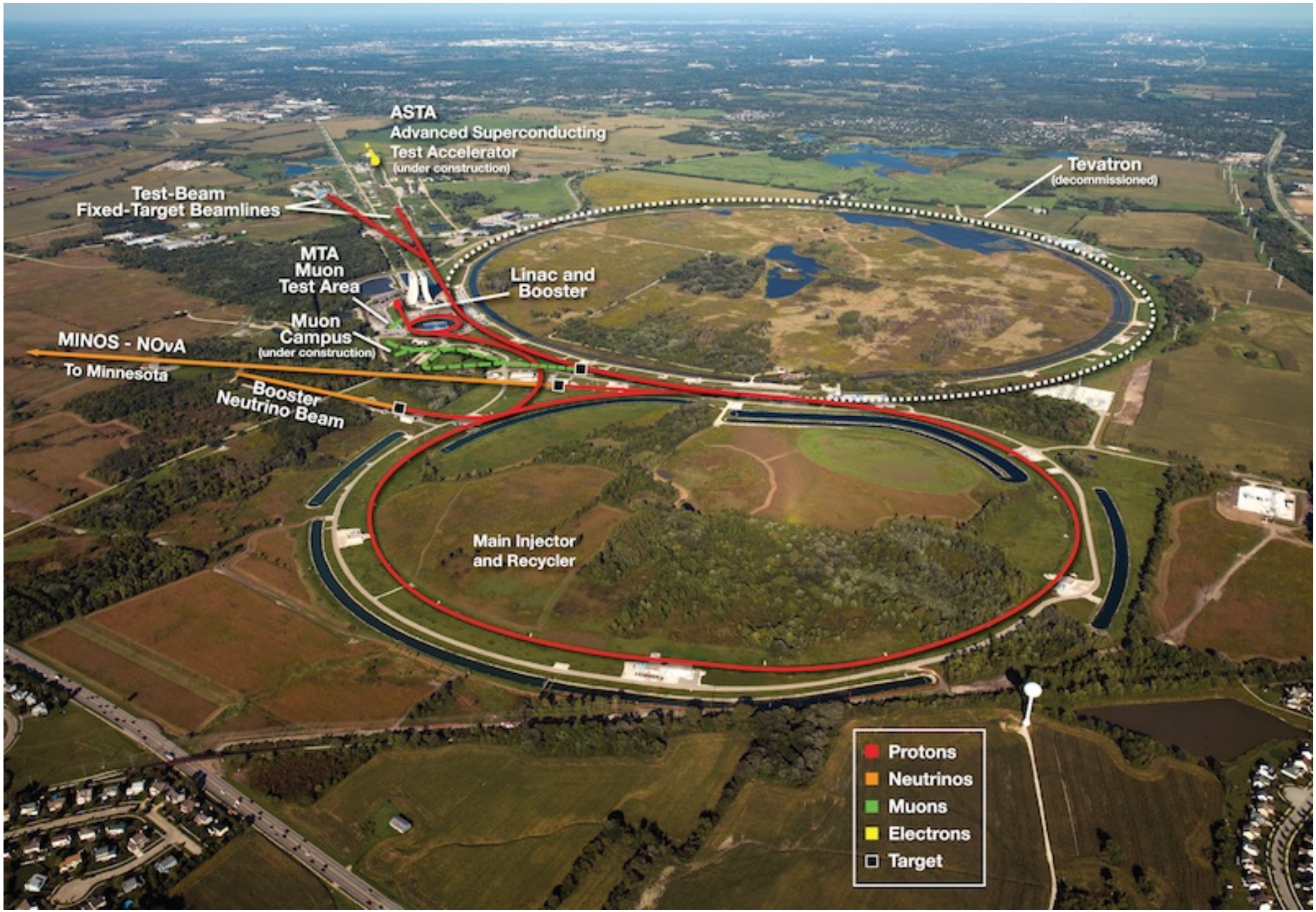
The Fermilab accelerator complex

Where is Fermilab?

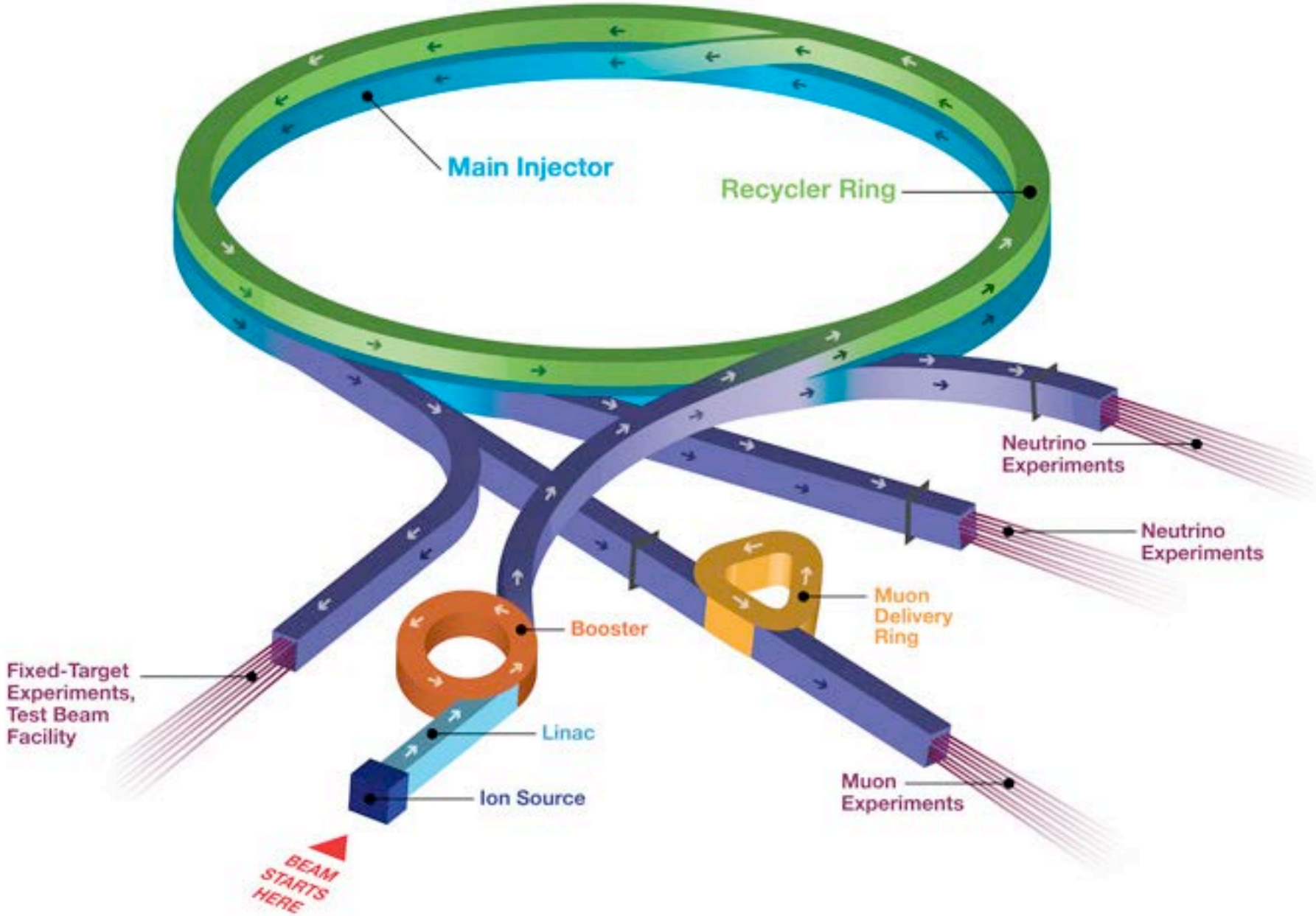


The Fermilab campus

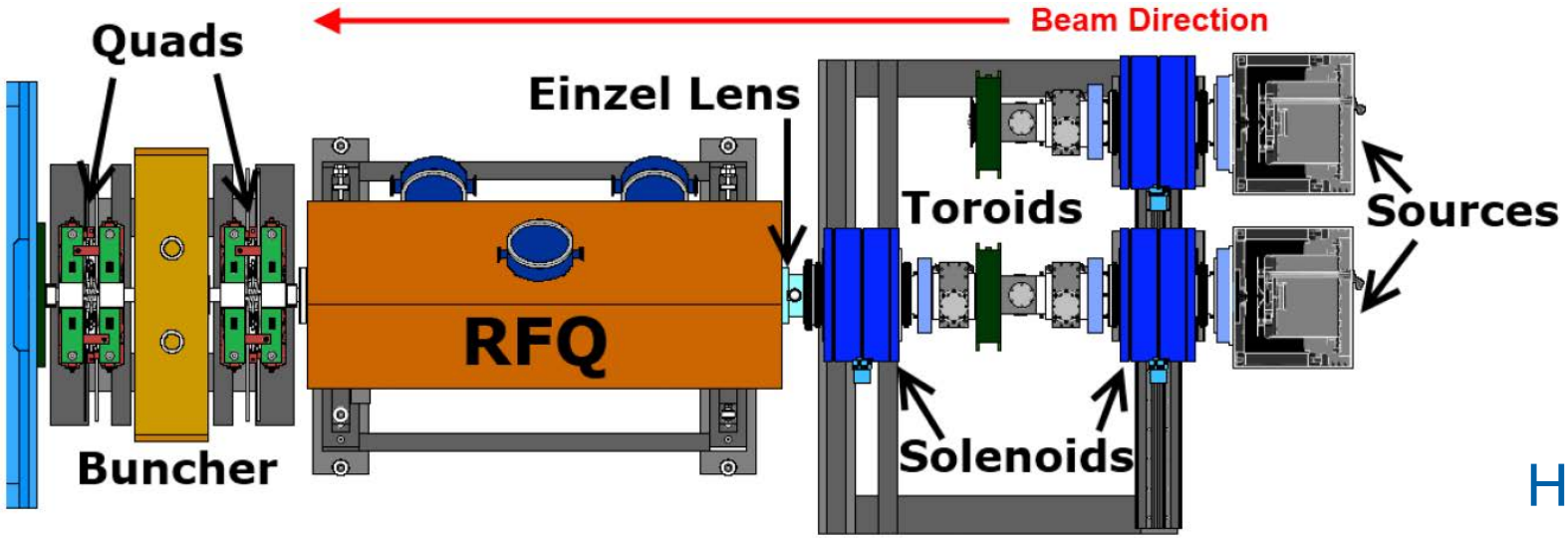
Fermilab accelerator complex

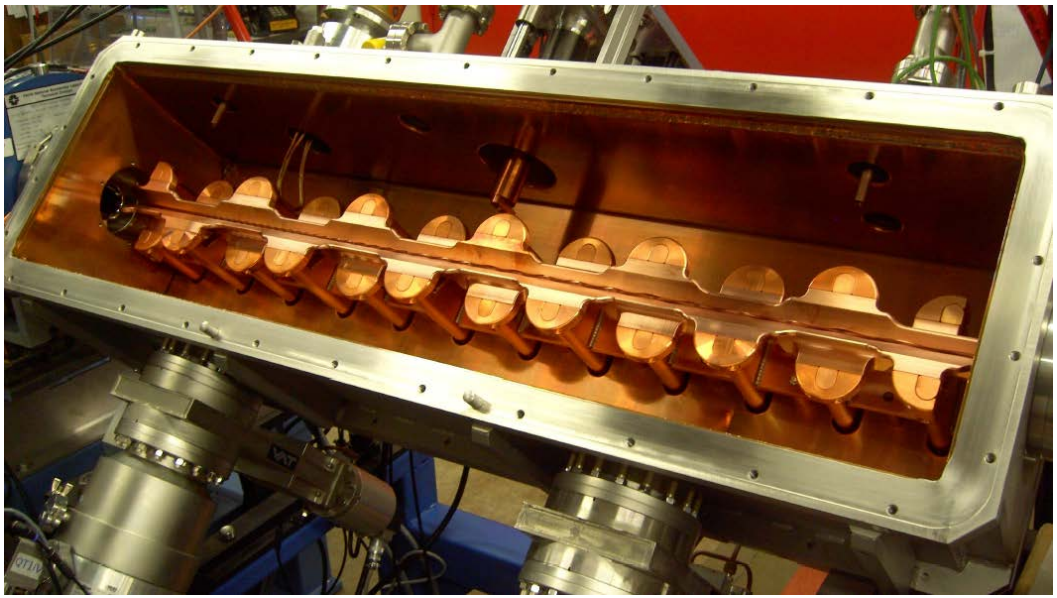


Fermilab Accelerator Complex



Ion source, radio-frequency quadrupole, beam transport





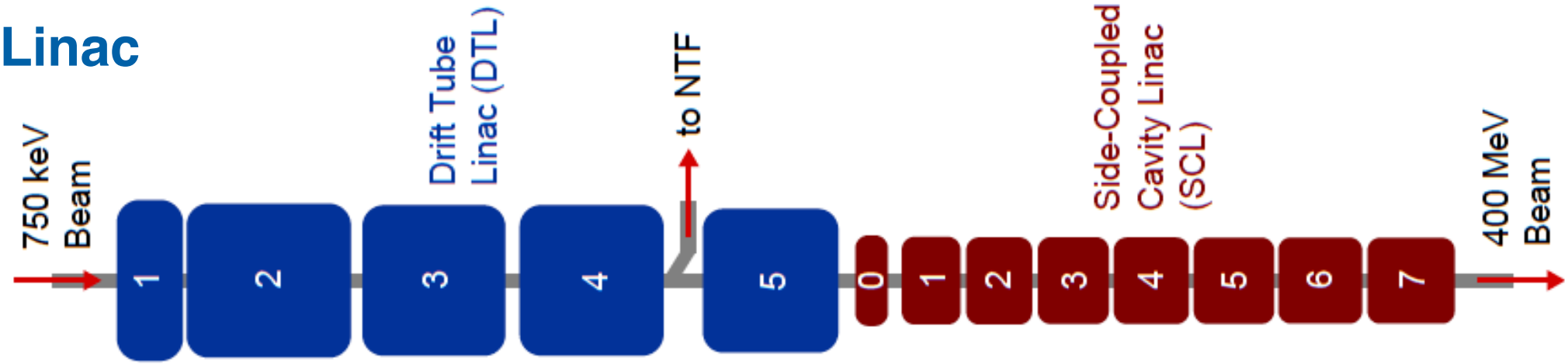
H^- sources

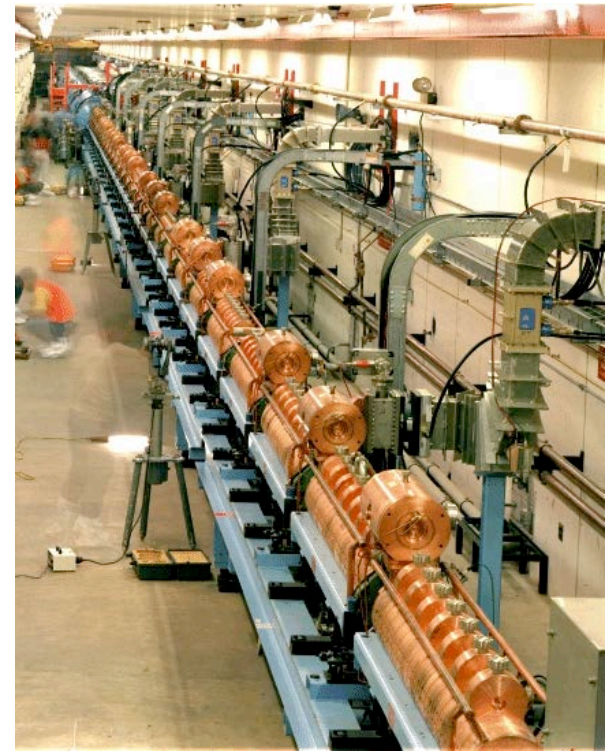
35 keV to 750 keV

65 mA

RFQ focuses and accelerates quickly to avoid space-charge blowup

Linac





Serves Booster, Neutron Therapy Facility, and Muon Test Area

Booster

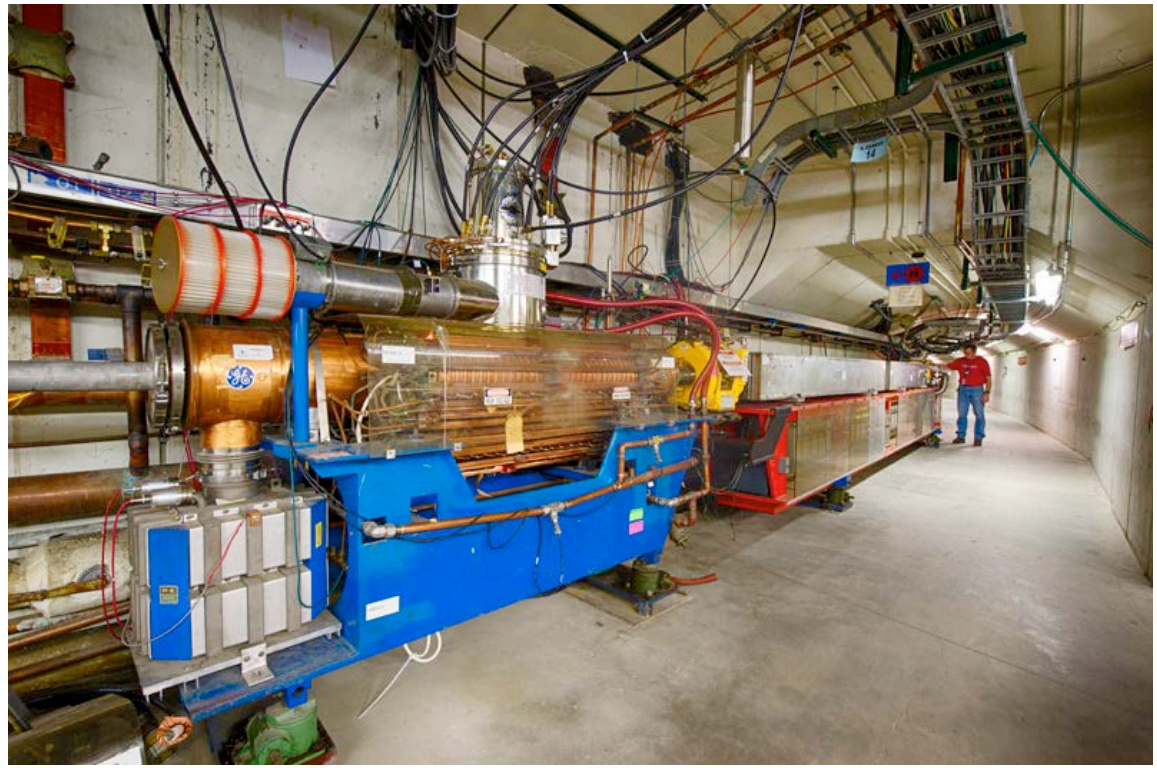
Stripping injection (H^- to protons)

Combined-function magnets (steering and focusing)

Rapid-cycling synchrotron (15 Hz)

468 m circumference

400 MeV to 8 GeV

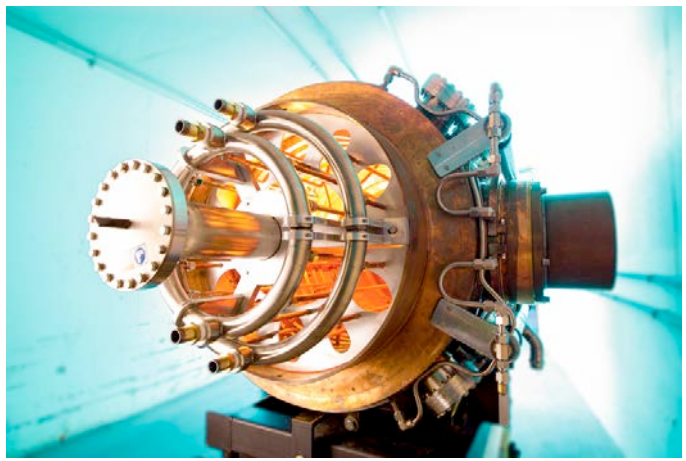


Delivers beam to Main Injector and to 8-GeV neutrino target

Recycler

Permanent magnets
Fixed 8-GeV energy
3.3 km circumference

Accumulates protons during
Main Injector ramp

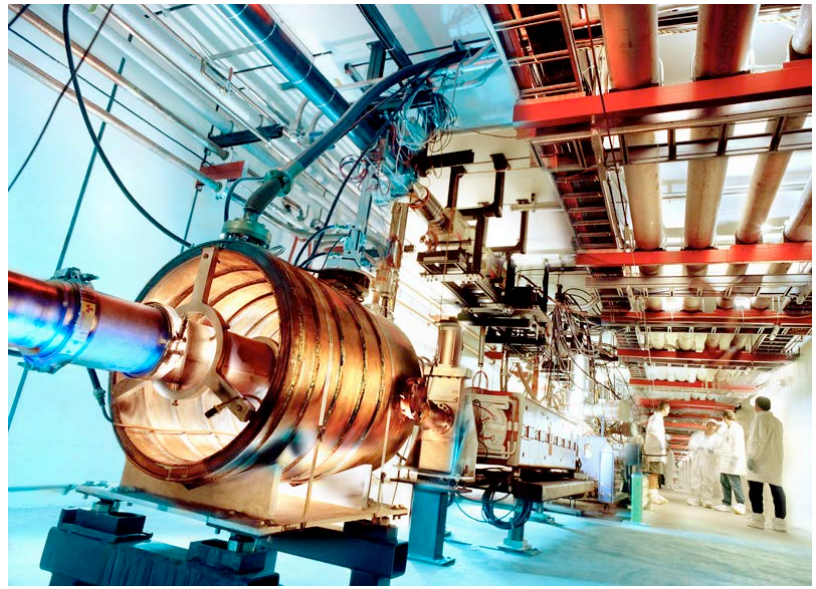


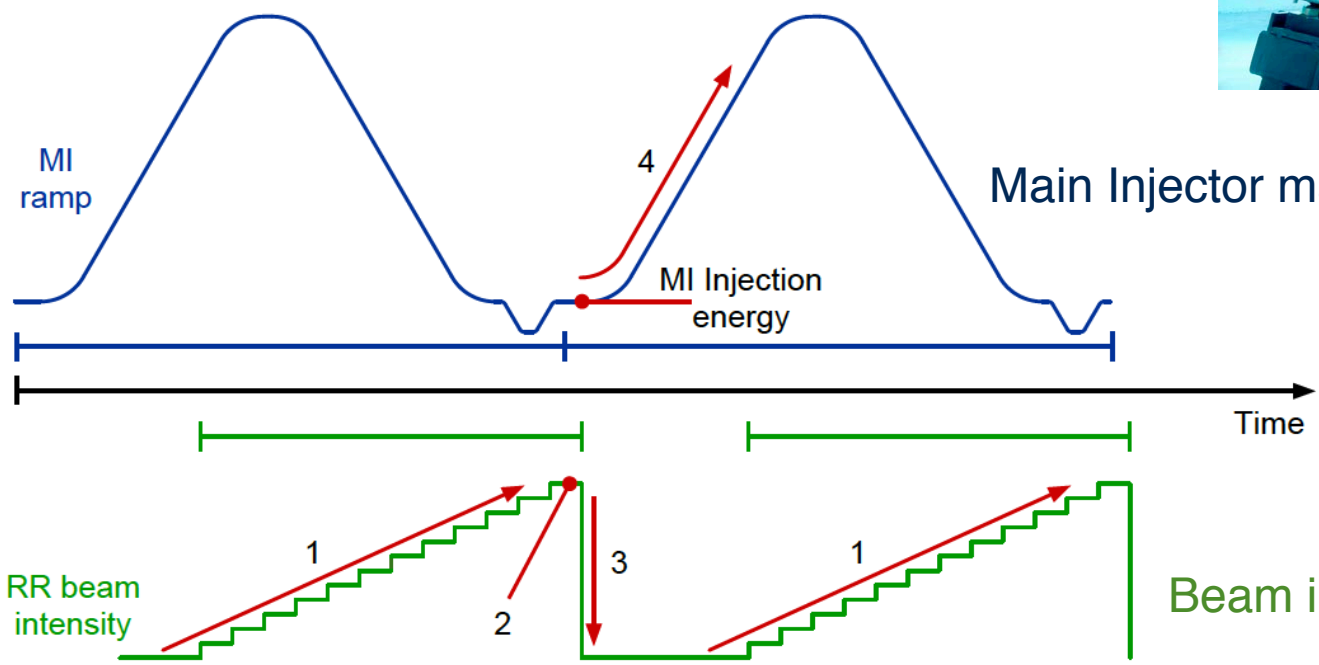
Main Injector

Ramping synchrotron (1.3 s)

8 GeV to 120 GeV

3.3 km circumference





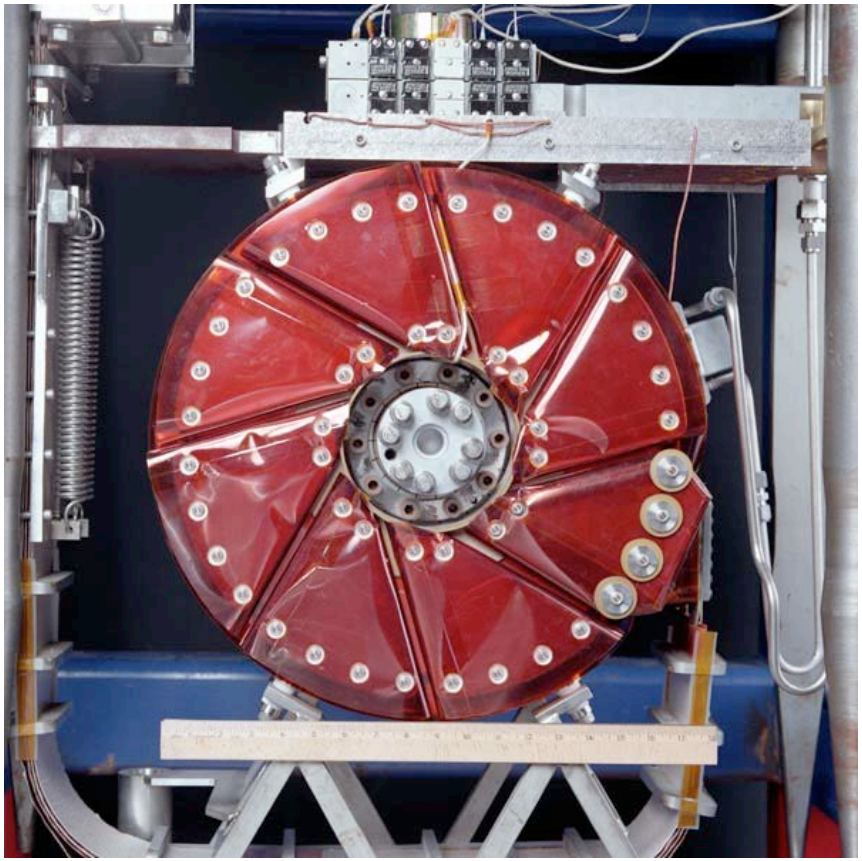
Main Injector magnet ramp

Beam intensity in Recycler

Fast extraction to neutrino target (450 kW record so far)

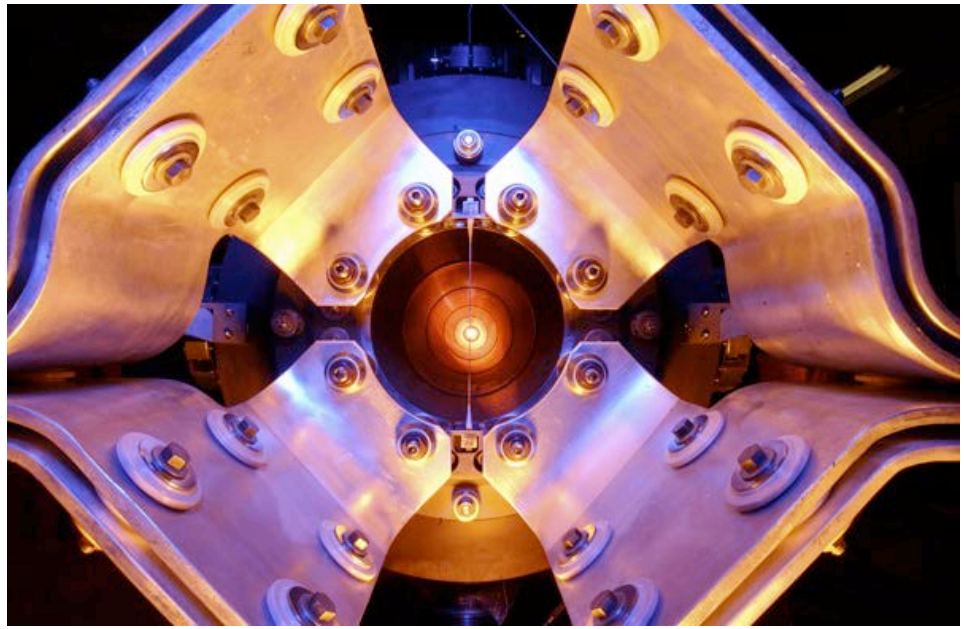
Slow resonant extraction to fixed-target experiments

Target stations



Lithium lens was used for antiproton production

NuMI horn



Challenges:
energy deposition, kW to MW
activation

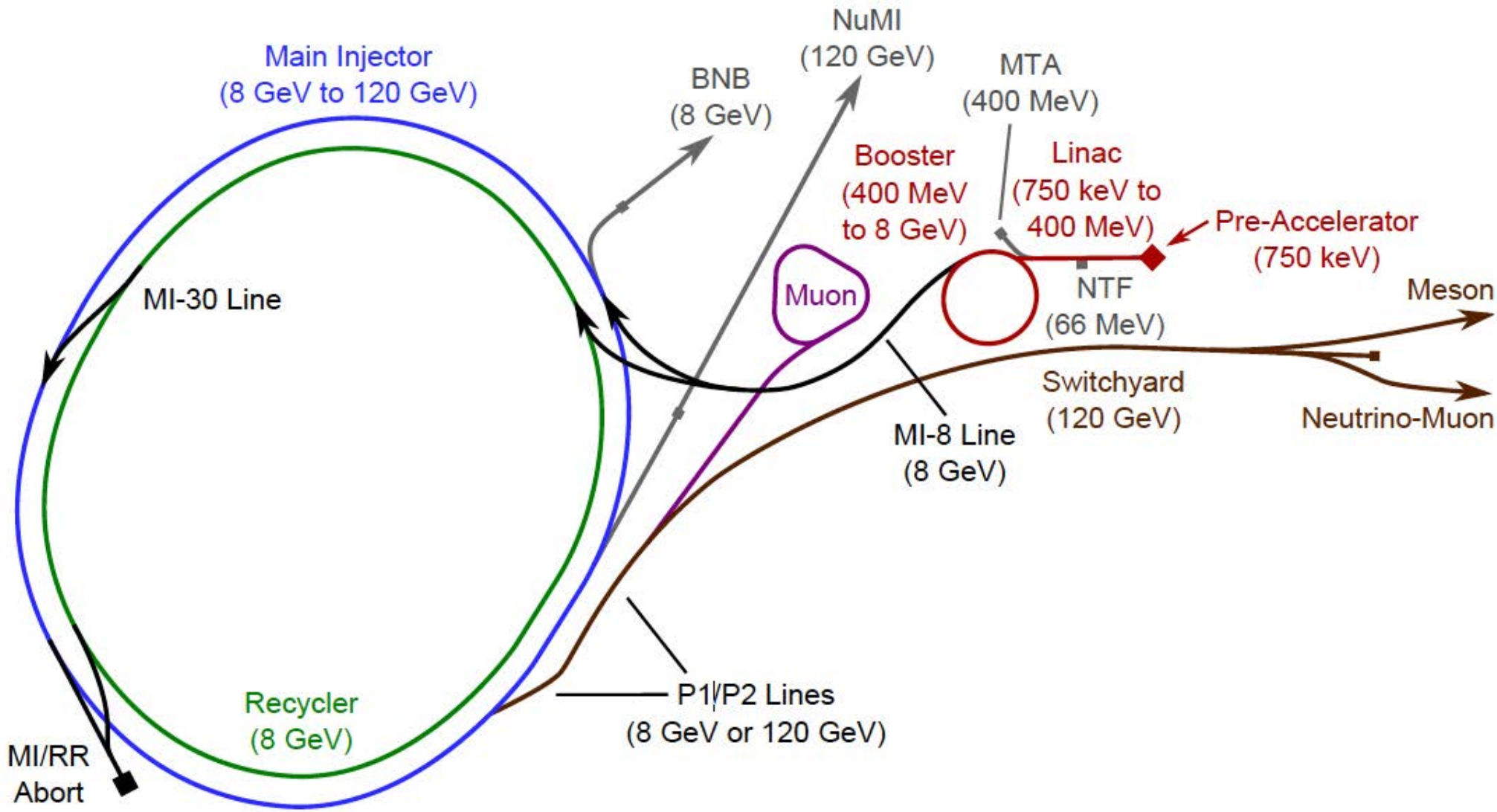
Muon Delivery Ring

Storage ring

474 m circumference

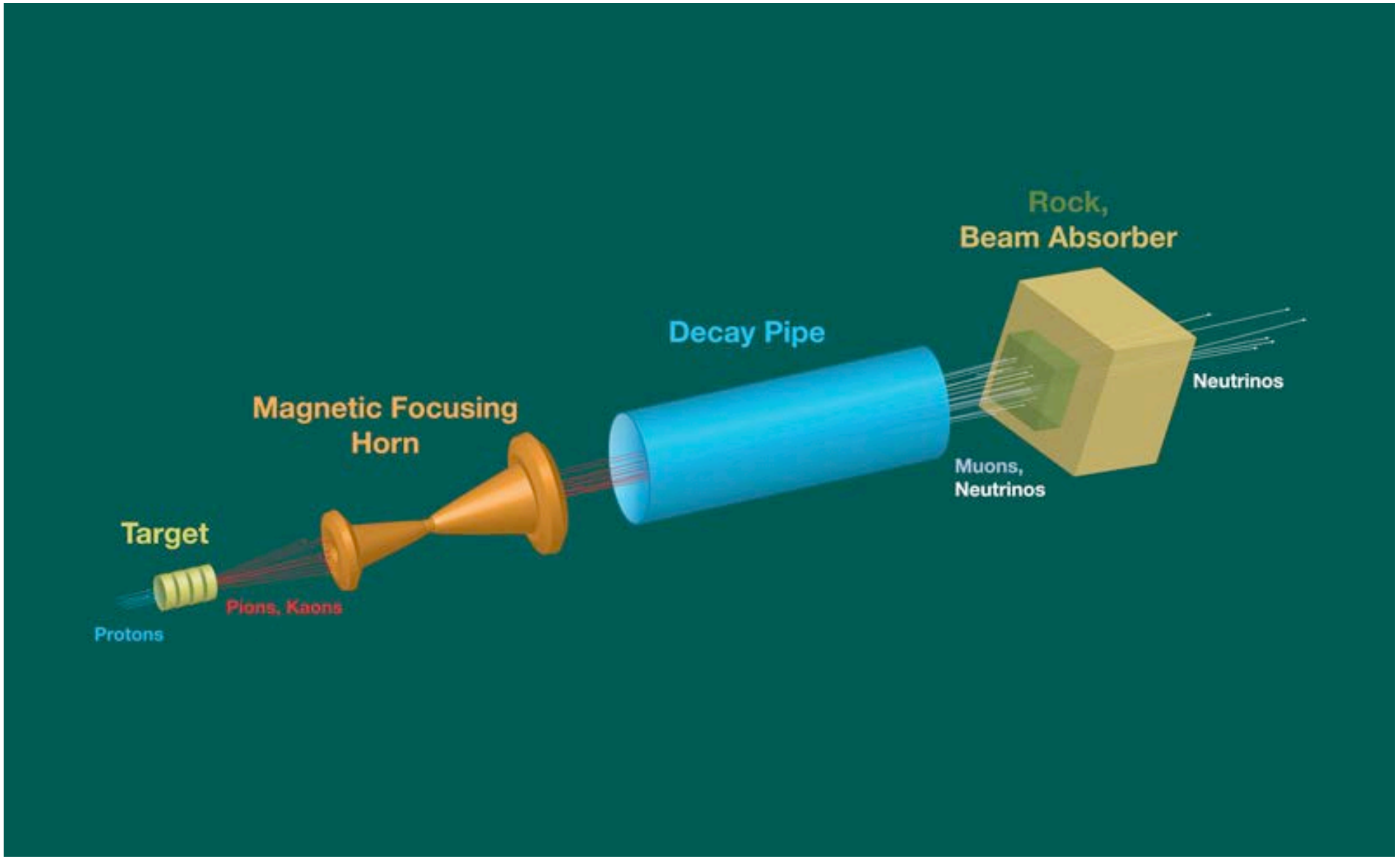
Will be used to separate muons from other particles in a few turns

The Fermilab accelerator complex in more detail



<http://www-bdnew.fnal.gov/operations/rookie_books/rbooks.html>

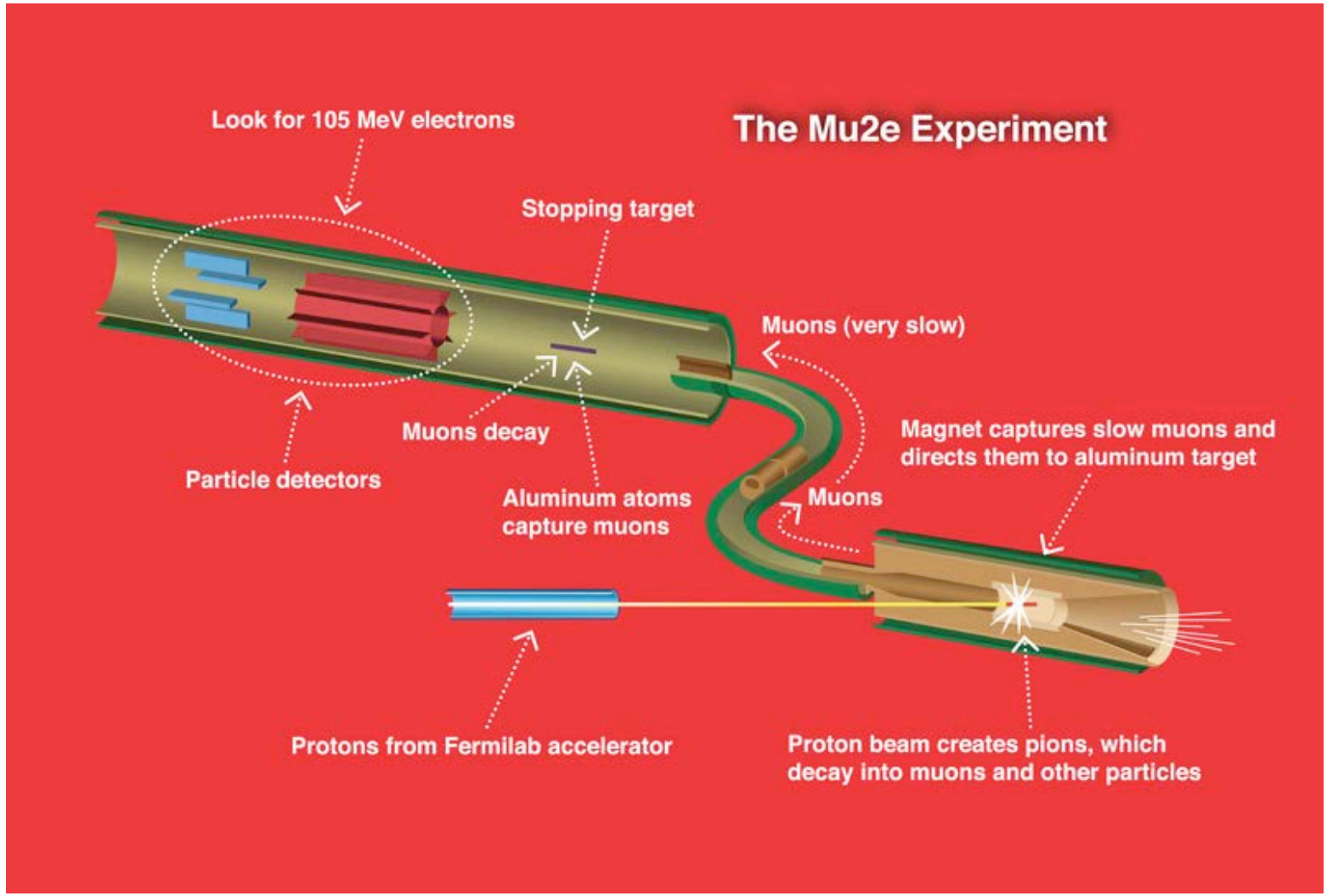
Neutrino beam lines



Muon g-2 experiment

muon-g-2.fnal.gov

Muon-to-electron conversion experiment



mu2e.fnal.gov

Limitations and challenges

- Study of neutrinos and rare decays requires intense primary beams
  - particle **losses** and **activation** must be minimized
  - **energy deposition** can damage components
  - beam **instabilities** limit maximum intensity

Accelerator technologies at Fermilab

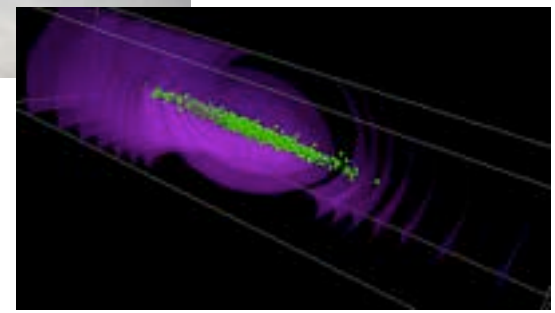
Accelerator technologies at Fermilab

- Superconducting radiofrequency cavities

- Superconducting magnets

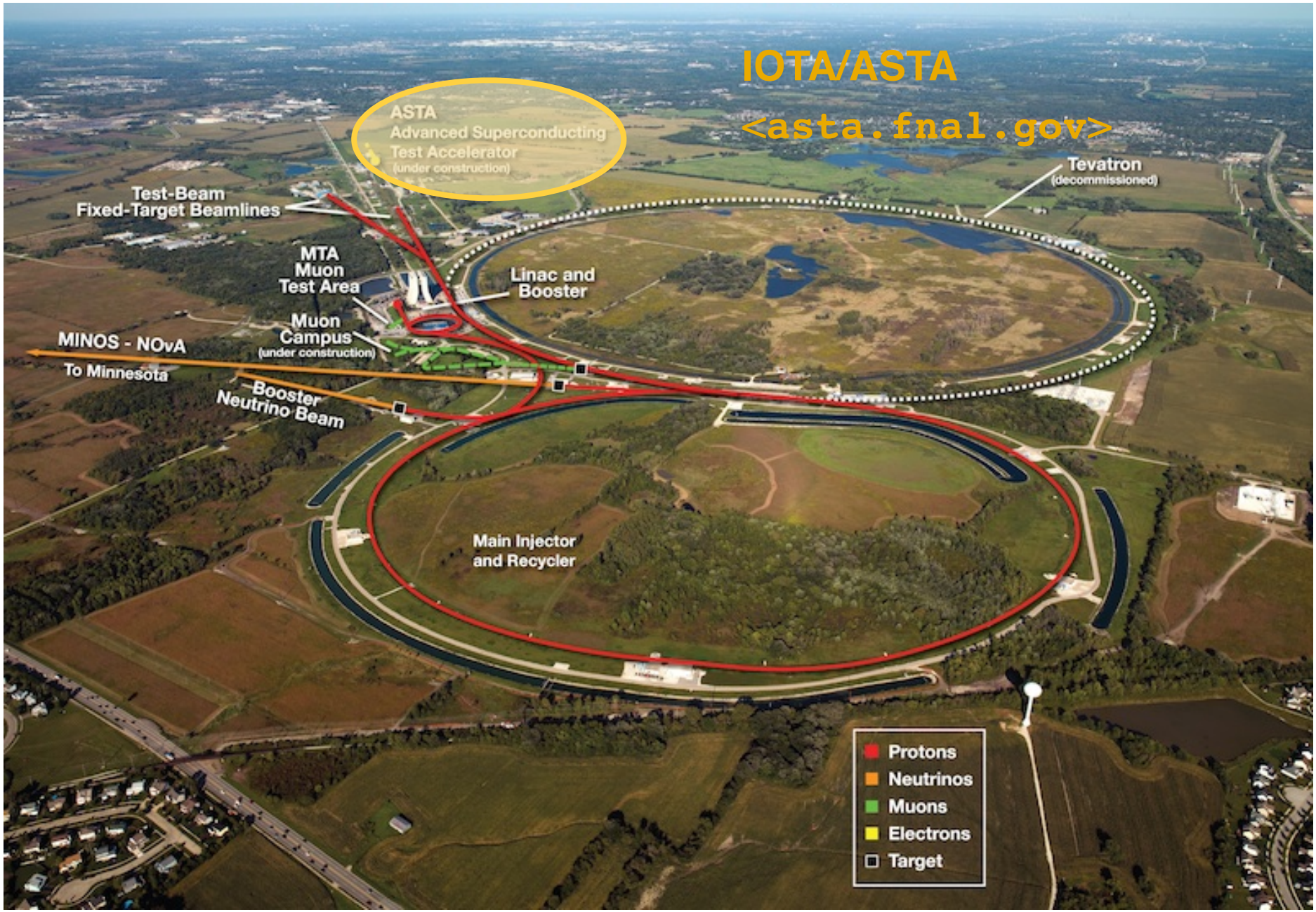
- Power targets

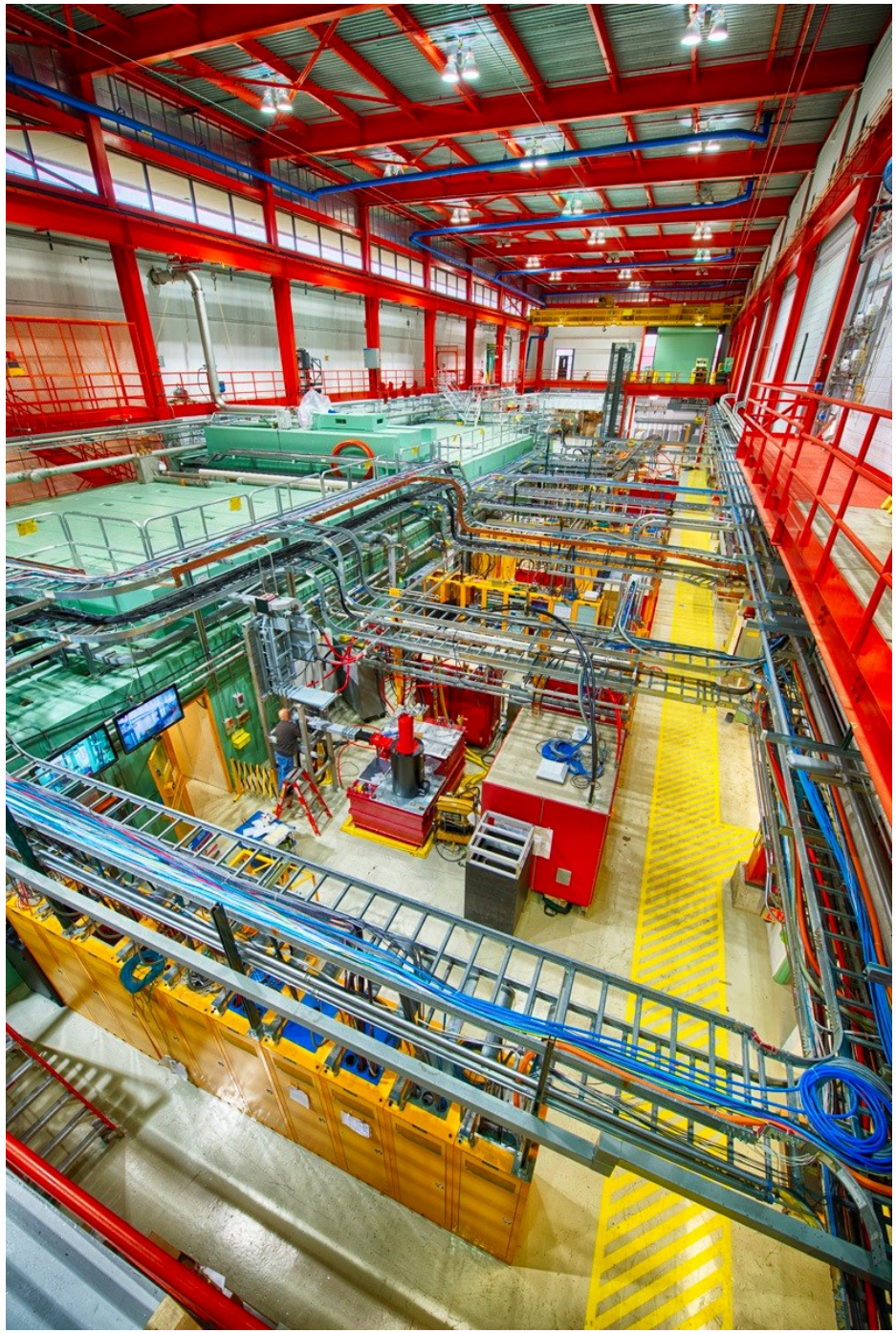
- Scientific computing



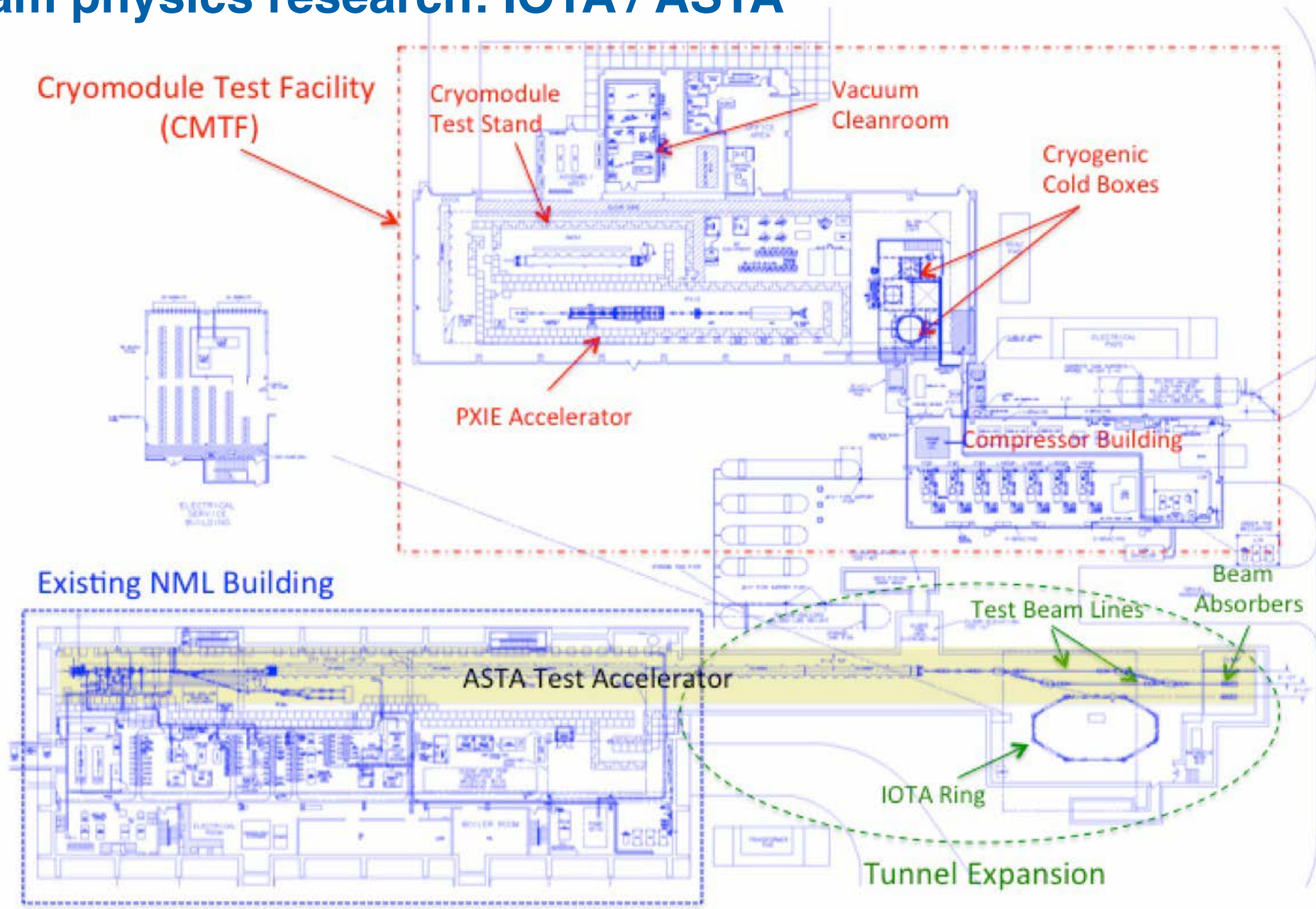
Beam physics research

Beam physics research facility

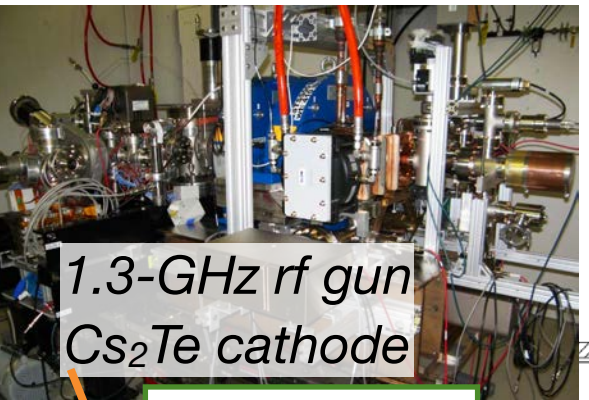




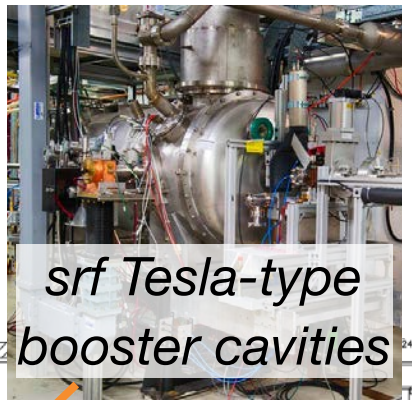
Beam physics research: IOTA / ASTA



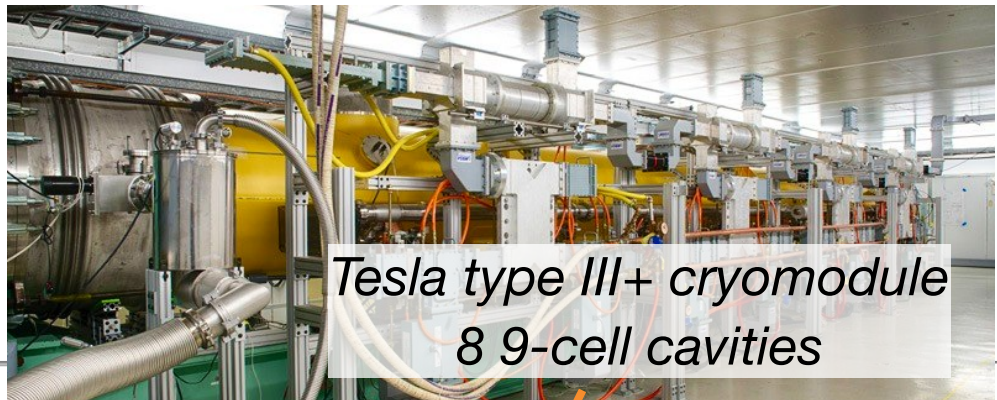
ASTA photoinjector



1.3-GHz rf gun
Cs_2Te cathode



srf Tesla-type
booster cavities

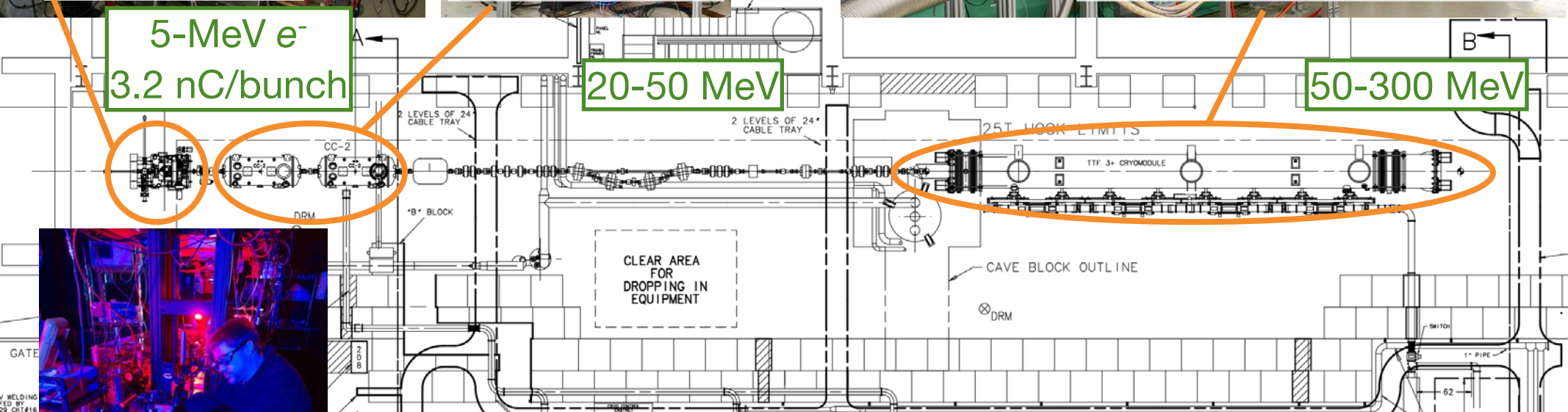


Tesla type III+ cryomodule
8 9-cell cavities

5-MeV e^-
3.2 nC/bunch

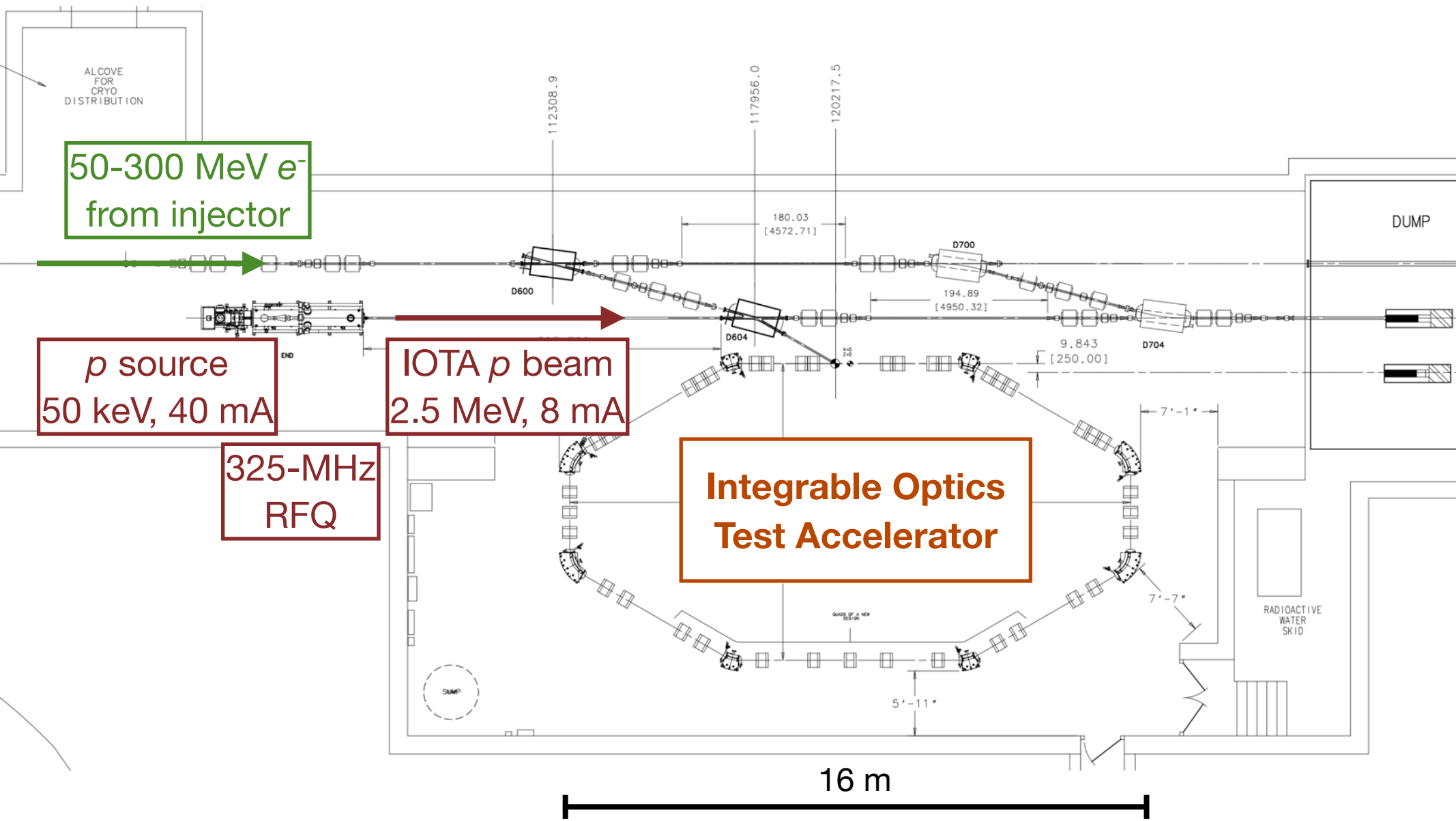
20-50 MeV

50-300 MeV



263-nm laser
3000 micropulses @ 3 MHz
5 Hz rep. rate

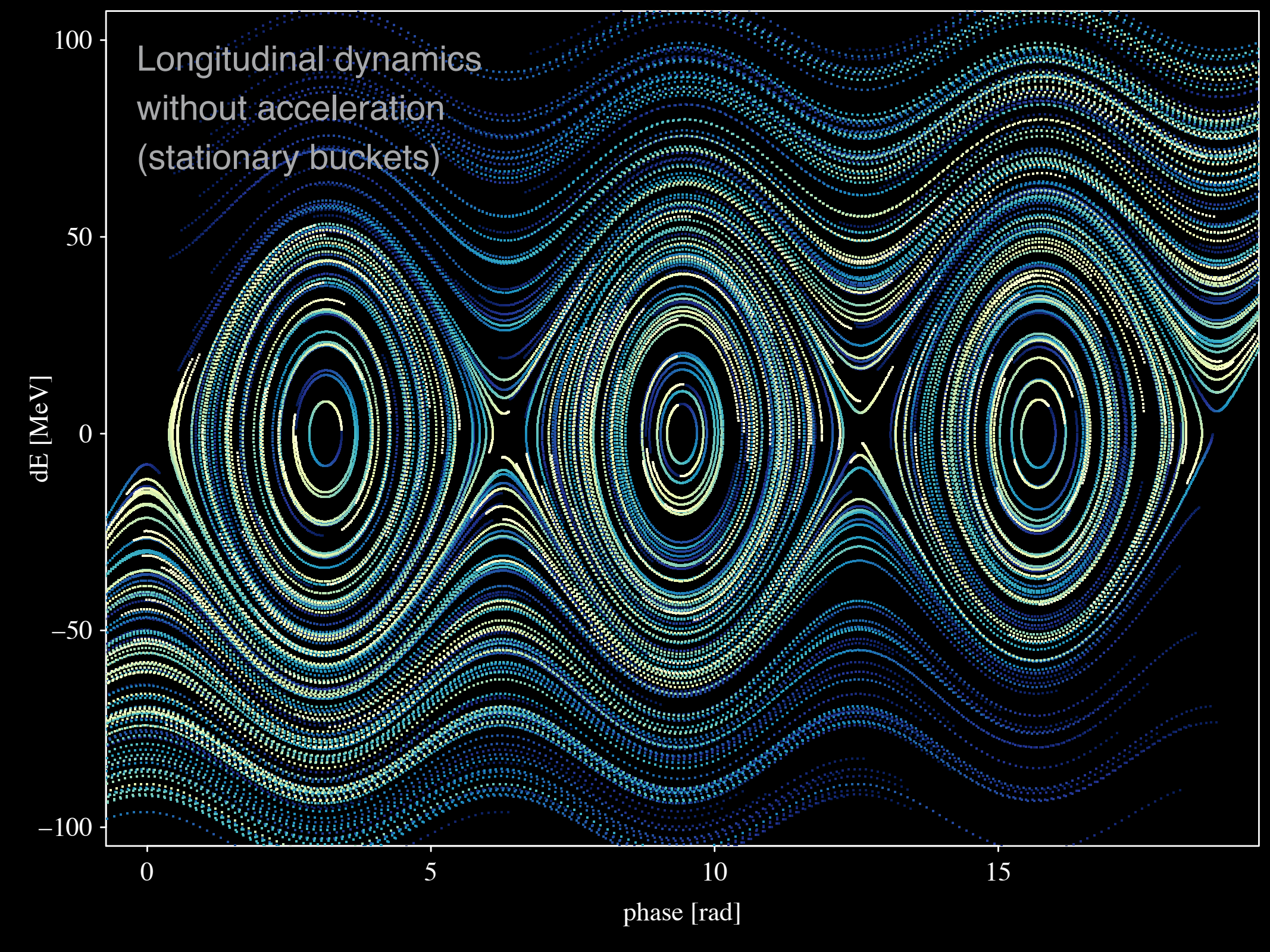
High-energy beam lines and IOTA (under construction)

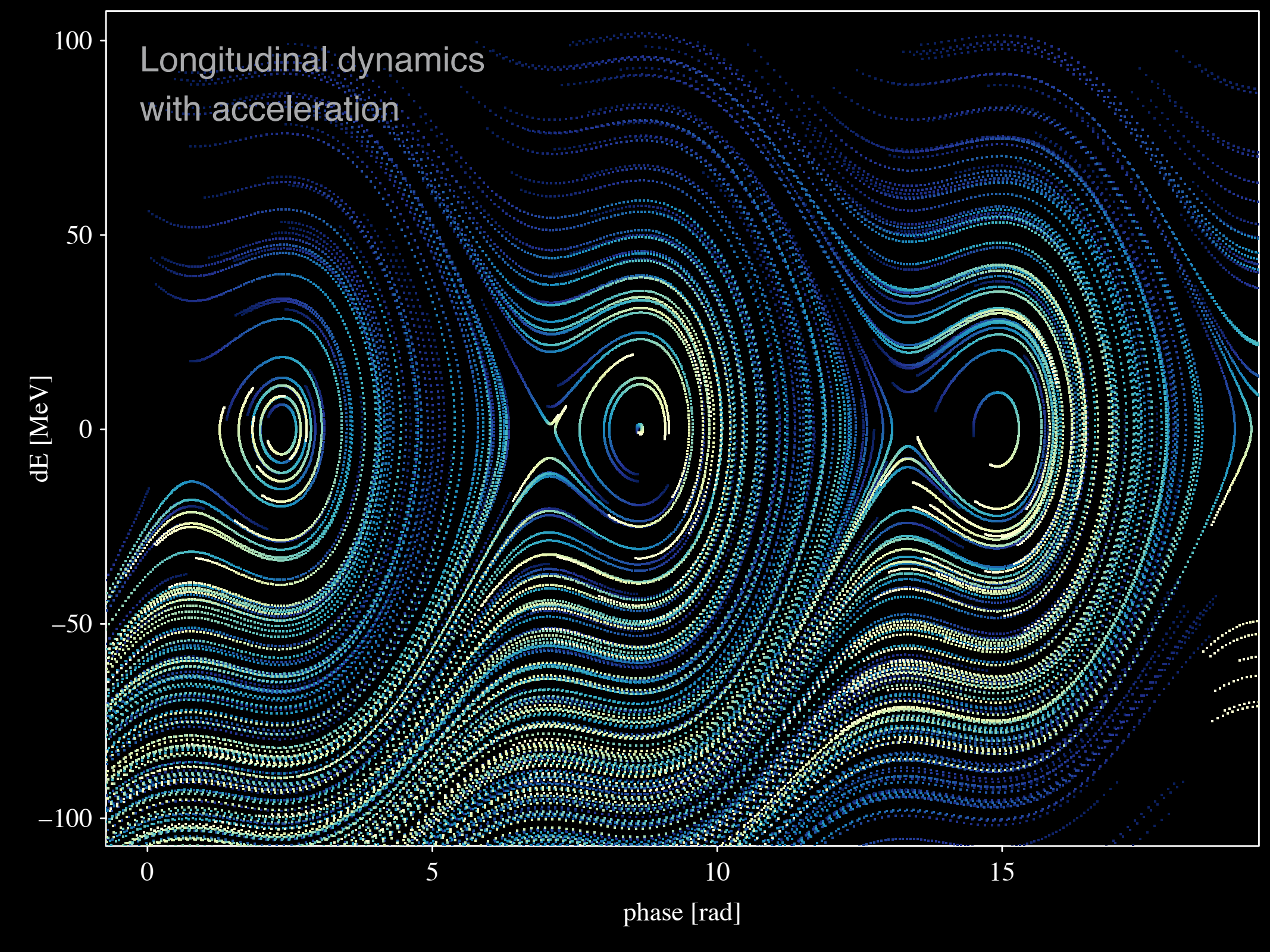


Main research areas

- In general, what kinds of dynamical systems are stable and robust against perturbations?
- Can intrinsically nonlinear accelerators be designed, built, and operated?
- Will nonlinear integrable lattices allow accelerators to exceed their present intensity limitations?
- Do we understand the dynamics of intense charged-particle beams under the influence of self fields?
- What kinds of radiation are generated by short electron pulses? What are their applications?

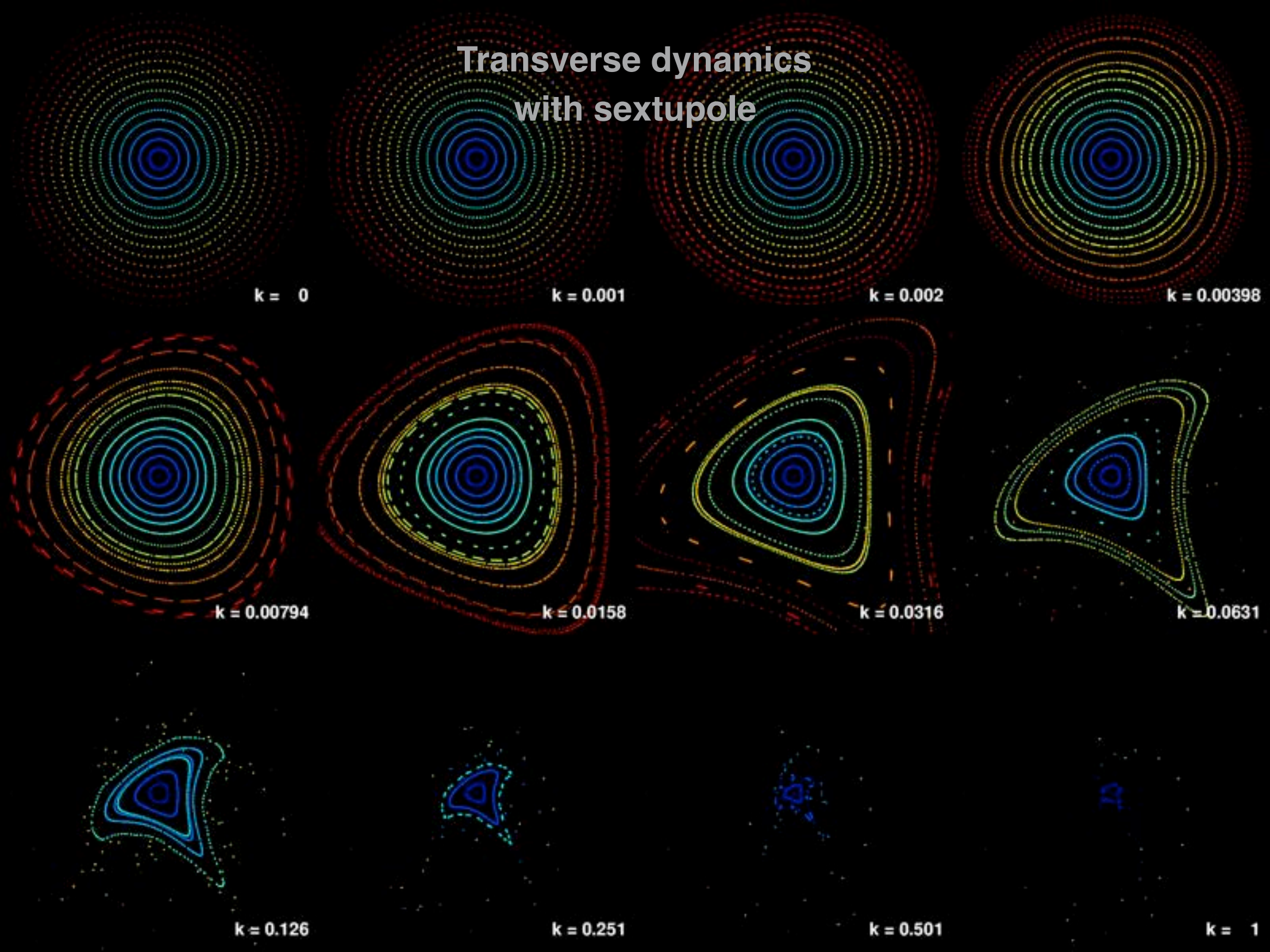
Longitudinal dynamics in rf fields


Longitudinal dynamics
without acceleration
(stationary buckets)
100
50
0
−50
−100
dE [MeV]
0
5
10
15
phase [rad]

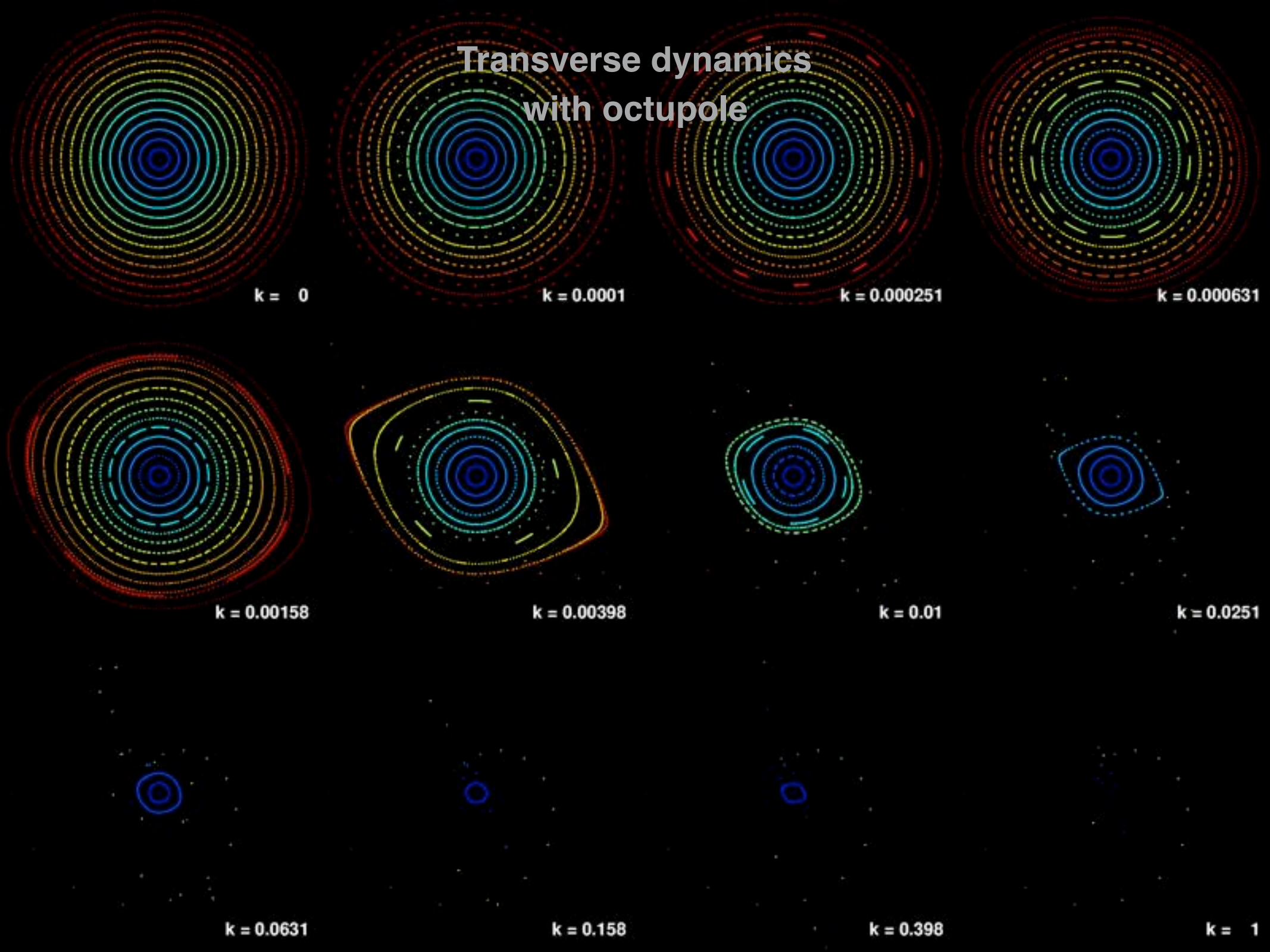

Longitudinal dynamics
with acceleration
100
50
0
−50
−100
dE [MeV]
0
5
10
15
phase [rad]

Nonlinear dynamics in accelerators

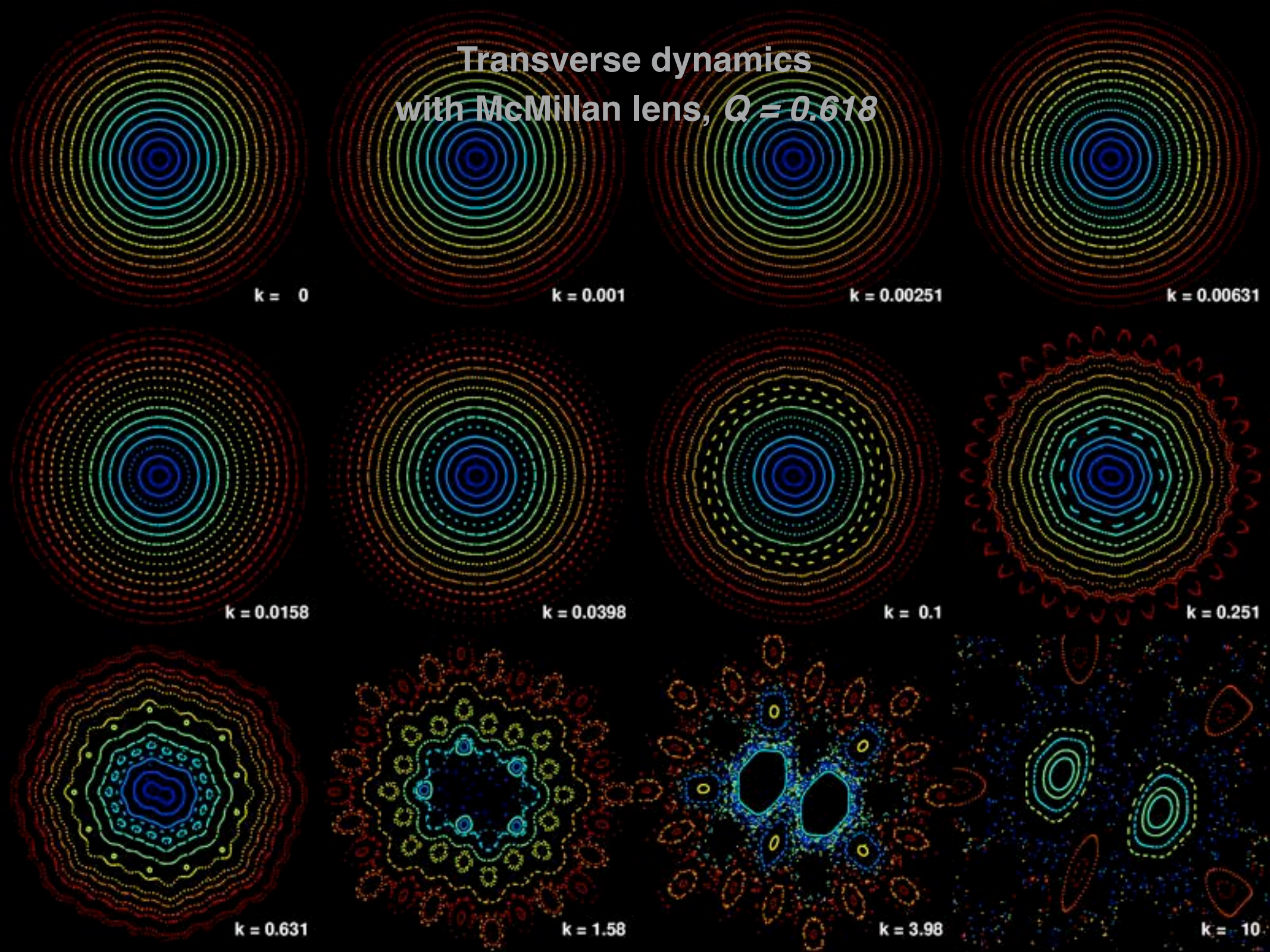
Transverse dynamics with sextupole



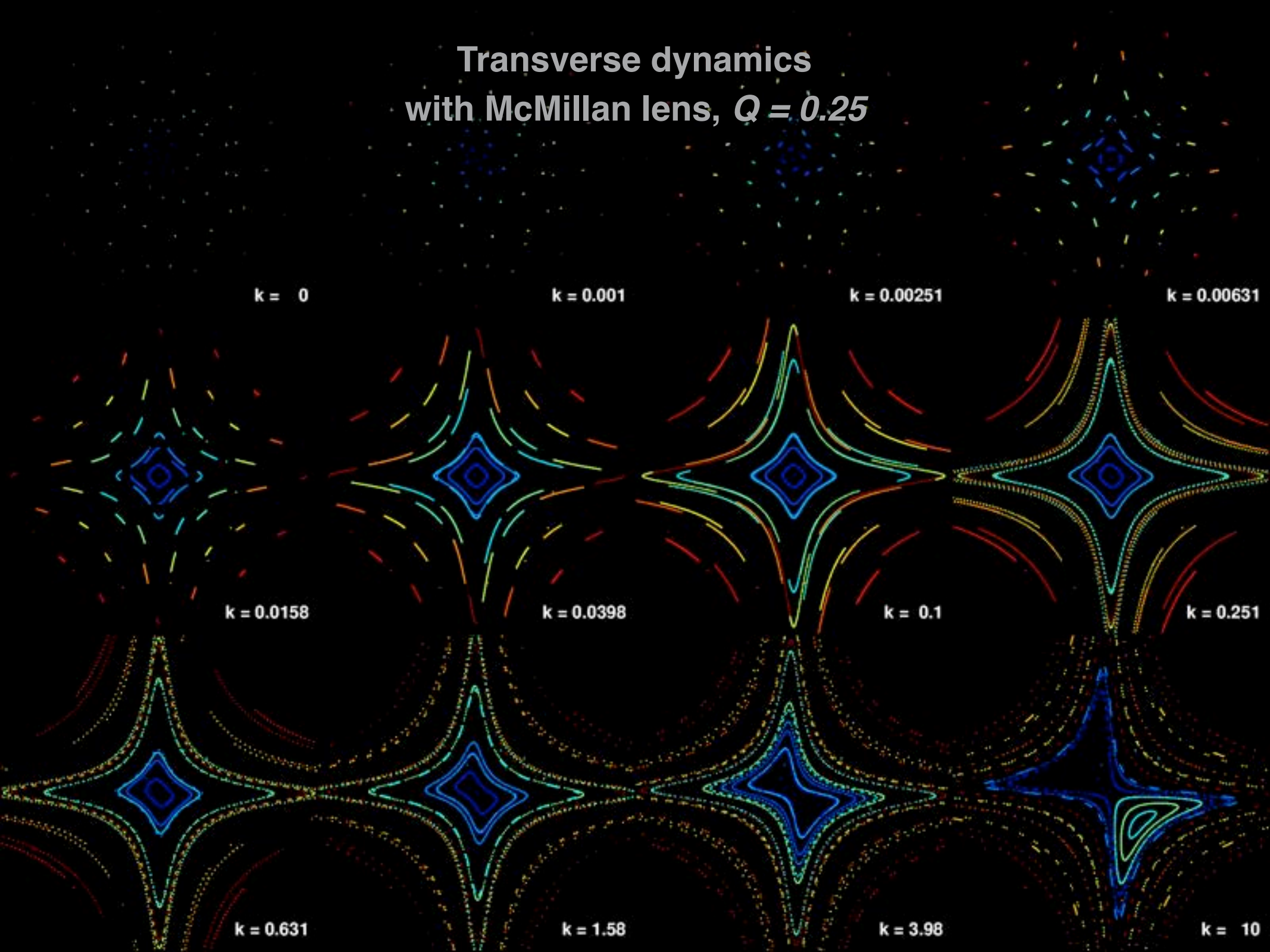
Transverse dynamics with octupole



Transverse dynamics with McMillan lens, $Q = 0.618$



Transverse dynamics with McMillan lens, *Q = 0.25*

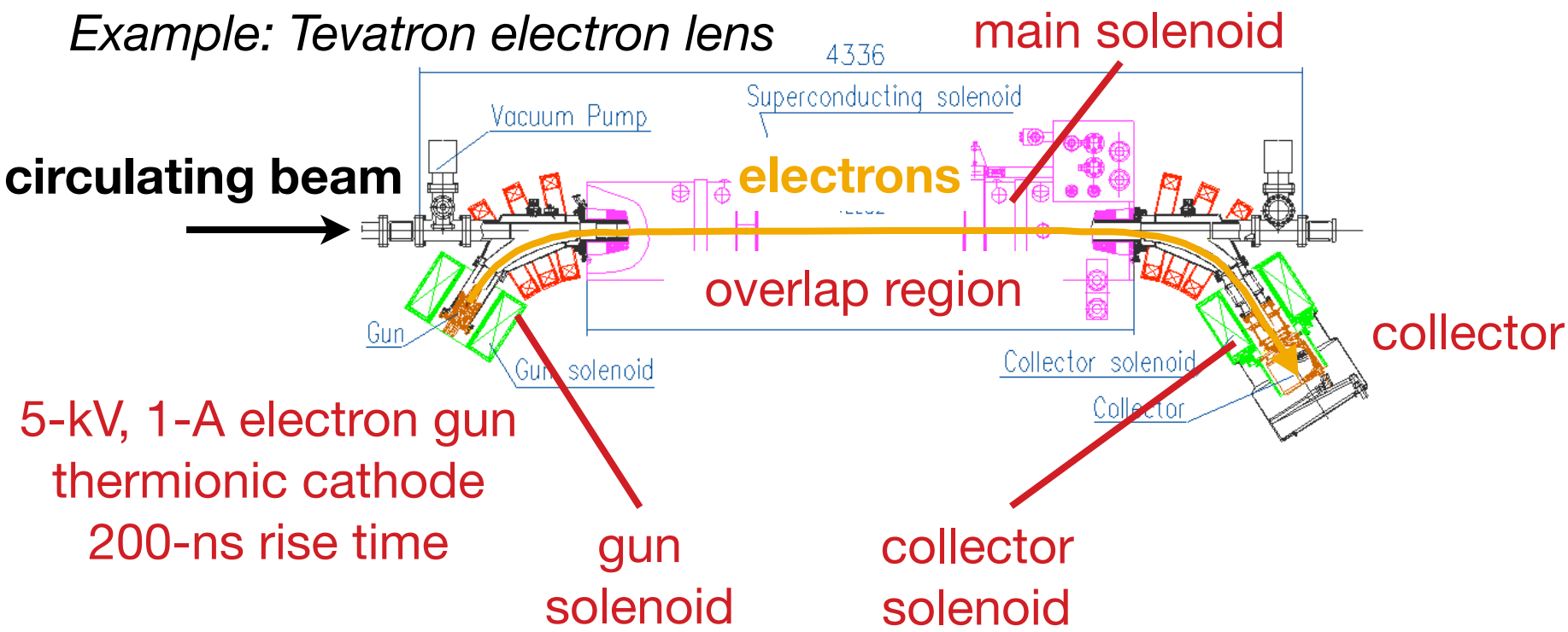


Space-charge fields and electron-beam lenses

What's an electron lens?

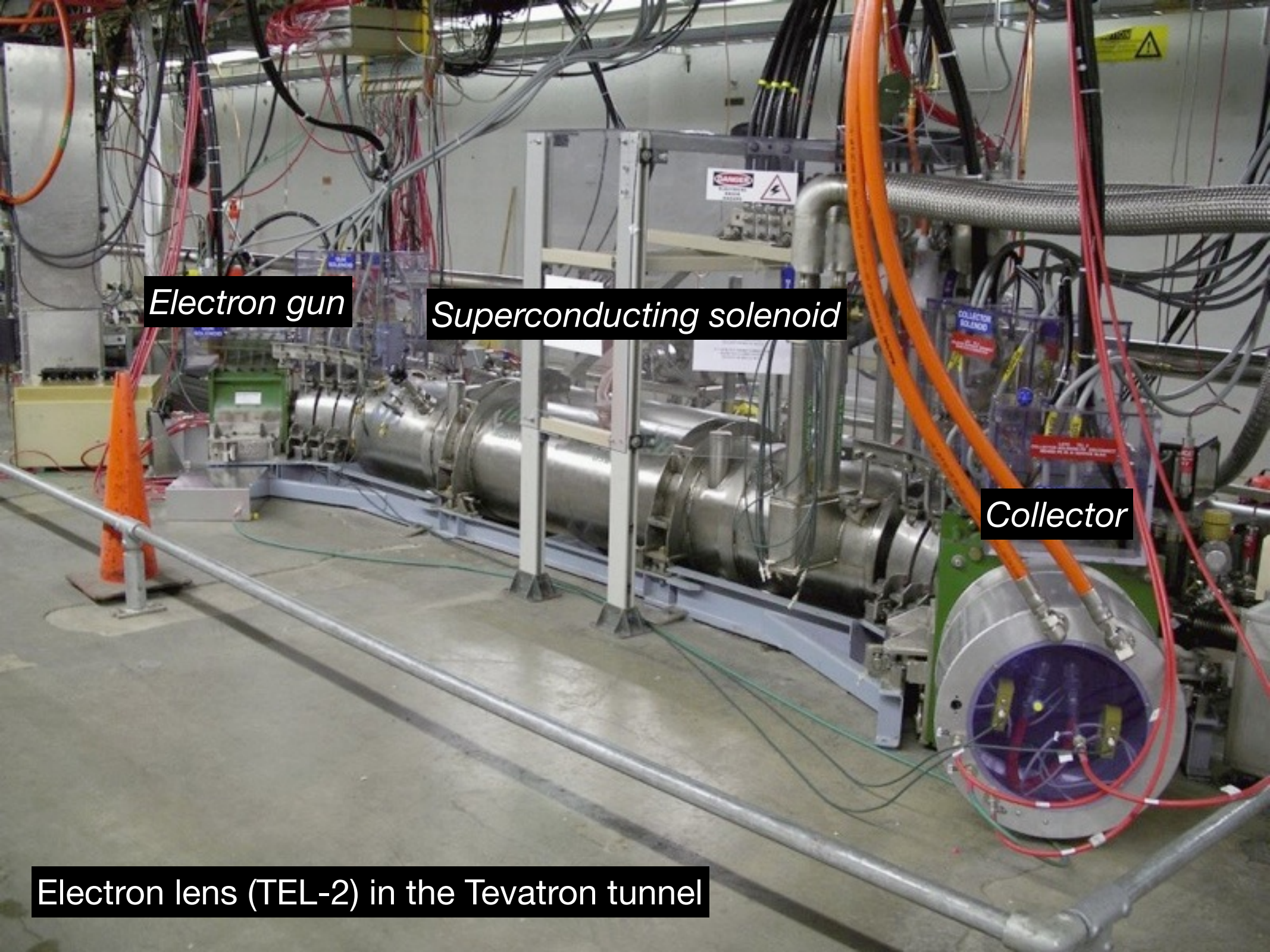
- Pulsed, magnetically confined, low-energy electron beam
- Circulating beam affected by electromagnetic fields generated by electrons
- Current-density profile shaped by cathode and electrode geometry
- Stability provided by strong axial magnetic fields

Example: Tevatron electron lens



For IOTA, we plan to use a resistive solenoid in the overlap region

Shiltsev et al., Phys. Rev. ST Accel. Beams **11**, 103501 (2008)



Electron lens (TEL-2) in the Tevatron tunnel

Applications of electron lenses

In the Fermilab Tevatron collider

- ***long-range beam-beam compensation (tune shift of individual bunches)***
  - Shiltsev et al., Phys. Rev. Lett. **99**, 244801 (2007)
- ***abort-gap cleaning (for years of regular operations)***
  - Zhang et al., Phys. Rev. ST Accel. Beams **11**, 051002 (2008)
- ***studies of head-on beam-beam compensation***
  - Stancari and Valishev, FERMILAB-CONF-13-046-APC
- ***demonstration of halo scraping with hollow electron beams***
  - Stancari et al., Phys. Rev. Lett. **107**, 084802 (2011)

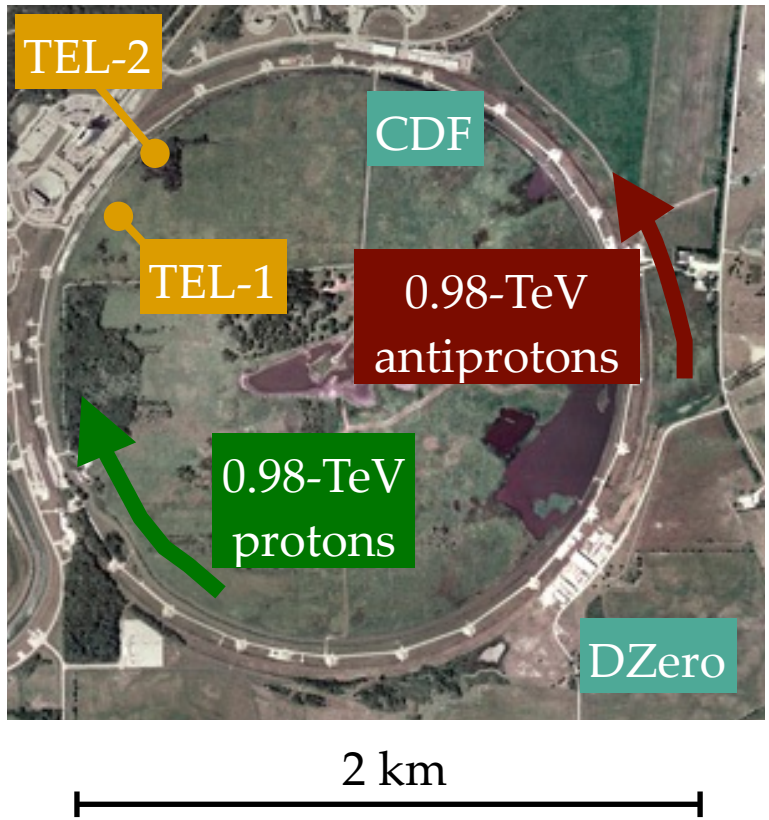
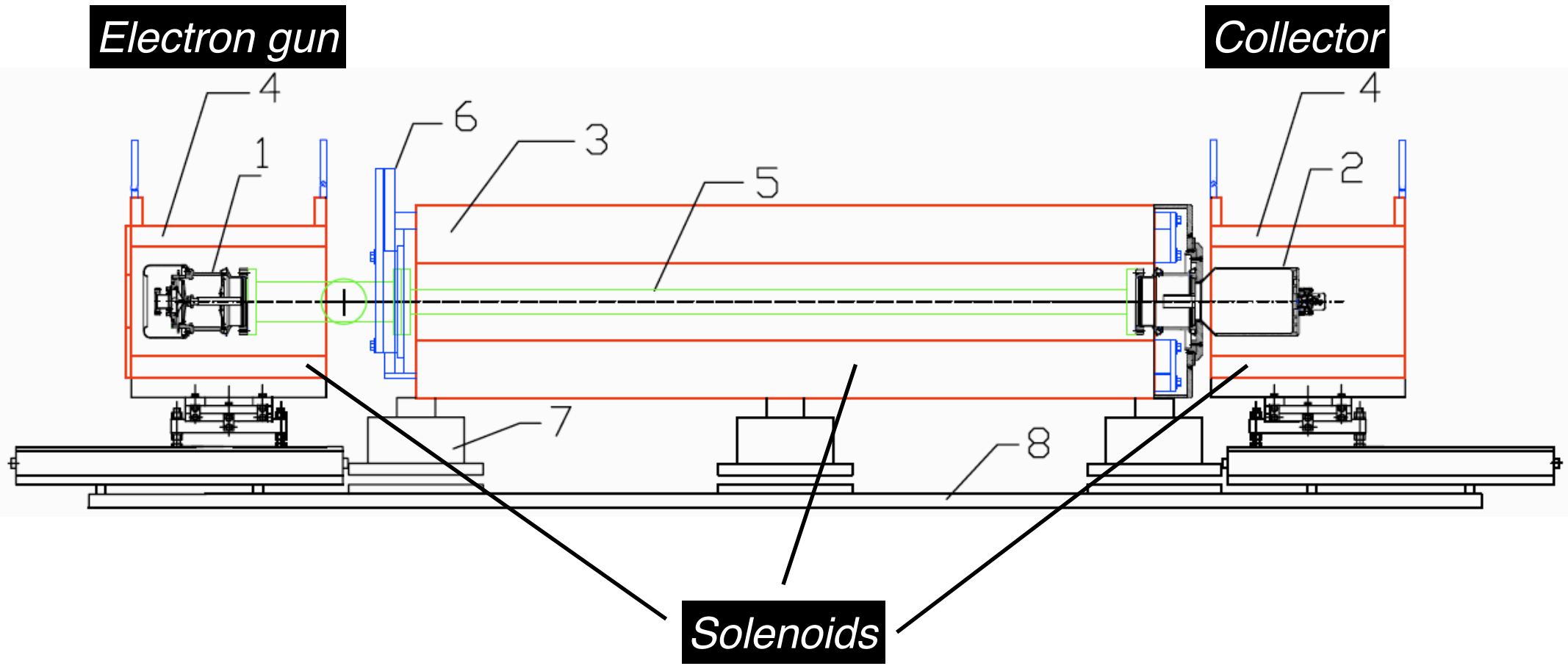
Presently, used in RHIC at BNL for head-on beam-beam compensation, luminosity improvements

- G. Robert-Demolaize, X. Gu, IPAC15

Current areas of research

- ***generation of nonlinear integrable lattices*** in the Fermilab Integrable Optics Test Accelerator
- ***hollow electron beam scraping*** of protons in LHC
  - R. Bruce, IPAC15
- ***long-range beam-beam compensation*** as charged, current-carrying "wires" for LHC
  - A. Valishev, IPAC15
- to ***generate tune spread for Landau damping*** of instabilities before collisions in LHC

Tevatron electron lenses



The Fermilab electron-lens test stand